Artículo de investigación

Problem of cryogenic cooling of semiconductor switches for power convertors

Проблема криогенного охлаждения полупроводниковых переключателей для силовых преобразователей

Recibido: 18 de julio del 2019 Aceptado: 29 de septiembre del 2019

Written by:

Kirill A. Modestov[156]

elibrary.ru: https://elibrary.ru/author_profile.asp?id=173979

https://www.scopus.com/authid/detail.uri?authorId=7801503830

Yury I. Kovan[157]

elibrary.ru: https://elibrary.ru/author_profile.asp?id=961131

Konstantin L. Kovalev[158]

elibrary.ru: https://elibrary.ru/author_profile.asp?id=24988

https://www.scopus.com/authid/detail.uri?authorId=6701714096

Anatoly E. Larionov[159]

elibrary.ru: https://elibrary.ru/author_profile.asp?id=33022

https://www.scopus.com/authid/detail.uri?authorId=7102928501

Ludmila A. Egoshkina[160]

Abstract

Currently, in Russia and abroad there is a significant progress in the development and manufacturing of electromechanical devices based on high-temperature superconducting materials. These devices possess the specific power at liquid nitrogen cooling above 10 kW/kg. Semiconductor convertors, which normally are necessary to operate together with electromechanical converters, have the specific power not exceeding 1 kW/kg at forced cooling. Therefore, the problem of increasing of the specific power of both electromechanical and static electrical devices of mobile objects (especially at operating in the aerospace field) is very relevant. The paper is devoted to the cooling of semiconductor electronic switches for semiconductor power converters at liquid nitrogen environment. In this case the improvement of cooling efficiency leads to a significant increase of the heat-transfer factor and, as a consequence, decreasing the mass and size of the radiators, and total weight and size of the semiconductor converters. The calculations which were carried out according to the results of

Аннотация

В настоящее время в России и за рубежом достигнут определённый прогресс в области разработки и создания электромеханических преобразователей на базе высокотемпературных сверхпроводниковых материалов. Такие электрические машины обладают удельной мощностью свыше 10 кВт/кг при охлаждении их жидким азотом. Статические преобразовательные устройства, работающие совместно с электромеханическими преобразователями, обладают удельной мощностью, не превышающей, как правило, 1 кВт/кг при принудительном охлаждении. Поэтому задача повышения удельной мощности как электромеханических, так и статических полупроводниковых электроэнергетических устройств подвижных объектов, особенно при их эксплуатации в аэрокосмической области, является весьма актуальной. В настоящей работе рассматриваются вопросы охлаждения полупроводниковых вентилей статических преобразователей жидким азотом. Повышение эффективности

[156] PhD, Associated Professor, Moscow Aviation Institute (National Research University), Moscow, Russia.
[157] PhD, Associated Professor, Moscow Aviation Institute (National Research University), Moscow, Russia.
[158] Doctor, Professor, Moscow Aviation Institute (National Research University), Moscow, Russia.
[159] PhD, Associated Professor, Moscow Aviation Institute (National Research University), Moscow, Russia.
[160] PhD, Associated Professor, Moscow Aviation Institute (National Research University), Moscow, Russia.

the experiments showed that the use of cryogenic cooling allows increasing about ~100 times the specific power of the semiconductor converters. The researches have shown that the placement of semiconductor converter in the medium of liquid nitrogen is most perspective for real application.

Keywords: Cryogenic cooling, electromechanical devices, heat-transfer factor, semiconductor converter, specific power of semiconductor converters.

охлаждения при этом приводит к значительному возрастанию коэффициента теплоотдачи и, как следствие, к снижению массы и габаритов радиаторов, а следовательно, и всего преобразователя. Расчёты, проведенные по результатам эксперимента, показали, что применение криогенного охлаждения позволяет примерно в 50÷100 раз повысить величину относительной мощности преобразователя. Рассмотрение вопроса компоновки преобразовательного блока показало, что помещение его в зону захолаживания жидким азотом является наиболее перспективным.

Ключевые слова: коэффициент теплоотдачи, криогенное охлаждение, статические преобразовательные устройства, удельная мощность преобразователя, электромеханические преобразователи.

Introduction

The task of increasing capacity in a single volume is relevant for developers of electrical and electric power equipment. Particularly relevant task is the task of increasing the specific power for electromechanical and semiconductor power converter of moving objects, especially when they are used in the aerospace field.

Currently, in Russia and abroad, some there is a progress in the development and creation of electromechanical converters based on high-temperature superconducting materials (Dubensky, Kovalev, Larionoff, Modestov, Penkin, Poltavets, 2016; Kovalev, Penkin, Larionov, Modestov, Ivanov, Tulinova, Dubensky, Verzhbitsky, Kozub, 2016; Modestov, Kovalev, Dubensky, Zhuravlev, 2018). Such electric machines have a specific power of more than 10 kW/kg cooled by liquid nitrogen. However, at the same time, the implementation of such ultimate values of specific powers is ensured by a multiple increase in the current density in the windings of electrical machines. At the same time, it should be noted that the question of deep cooling of the converting technique is not fully considered in the literature.

Currently, semiconductor both uncontrolled and controlled switchs have been developed for very significant values of currents and voltages. The dimensions of the switch block of the device are largely determined by the size of the radiators. Thus, reducing losses in the switches will not only increase their current load, which, as it is known, is determined by the permissible temperature of the semiconductor crystal, but also reduce the dimensions of the device by reducing the required cooling surface, and therefore the dimensions of the radiator. Now in static converters, the specific power does not exceed 1 kW / kg with forced cooling (Musin, 2014).

The task of increasing the efficiency and specific power of semiconductor converters can be solved using the following:

- Intensive cooling systems;
- Low (cryogenic) forced cooling temperatures.

The loss reduction can be achieved under constant cooling conditions, for example, by connecting a large number of transistors in parallel, which leads to a proportional decrease in the output resistance and, consequently, the power loss of the switches. As it is known (Naivelt, 1985), cooling surface area S is directly proportional to the power dissipated by the radiator:

$$S = P_l / \alpha \, \Delta T_{ro}, \qquad (1),$$

where P_l is the power loss, α is the heat transfer coefficient, ΔT_{ro} is the permissible overheating of the radiator base relative to the environment.

It is also interesting to consider the improvement of cooling conditions, which leads to an increase in the heat transfer coefficient α. Most of all it is interesting to consider cooling with low temperature refrigerants, such as liquid nitrogen (77 K), neon (27 K), hydrogen (20 K). In recent years, much attention has been paid to developments related to the use of electromechanical converters based on the effect of superconductivity in power supply systems and electric propulsion systems of moving objects (sea vessels, land vehicles and fully electrified aircraft) (Levin, Alekseev, Kharitonov, Kovalev, 2010). Thus, it is assumed that on the aircraft there will be reserves of these refrigerants, which makes it worthwhile to use them in the semiconductor technology in the future.

Literature review

Investigations of semiconductor switches operating in cryogenic cooling conditions are being carried out abroad. In particular, the characteristics of power semiconductor diodes during cooling by various liquid gases are given in (Ward, Dawson, Zhu, Kirschman, Mueller, Hennessy, Mueller, Patterson, Dickman, Hammoud, 2003). It can be seen from the above results that under conditions of liquid nitrogen cooling, the threshold voltage U_0 increases by 1,5÷2 times, while the differential resistance R_d of the direct branch of the current – voltage characteristic decreases by 2,5÷3 times. The main losses in the diode from direct current are determined by the following expression (Dubensky, Kovan, 2017):

$$P_{main} = U_0 I_{av} + R_d k^2_{sh} I^2_{av}, \qquad (2)$$

where I_{av} is the average switches current, k_{sh} is the switch current shape factor, according to the results given in (Ward, Dawson, Zhu, Kirschman, Mueller, Hennessy, Mueller, Patterson, Dickman, Hammoud, 2003), it can be assumed that under operating conditions at cryogenic temperatures the losses in the switches can vary slightly or slightly decrease depending on real values R_d and I_{av}.

However, to study the effect of cryogenic refrigerants on the heat transfer coefficient characterizing the cooling conditions of the switch (1) is of interest.

Results and discussion

The authors conducted an experiment, the purpose of which was to determine the electrical and thermal parameters of transistors operating in conditions of cryogenic temperatures. Metal-oxide-semiconductor field effect transistor (MOSFET), type IRFP90N20D (Infineon, 2016) was used to study.

According to the circuit shown in the Figure 1a, the output characteristic of the transistor was measured in the saturation mode at room temperature and at the temperature of liquid nitrogen, as well as in the absence and presence of a magnetic field. It can be noted that there is almost no influence of the magnetic field on the output characteristic of the transistor both at room temperature and at liquid nitrogen temperature. On the other hand, a significant (almost three times) decrease in the voltage drop across the transistor at the temperature of liquid nitrogen can be noted, which leads to an adequate decrease in the power of direct current losses (Figure 1b).

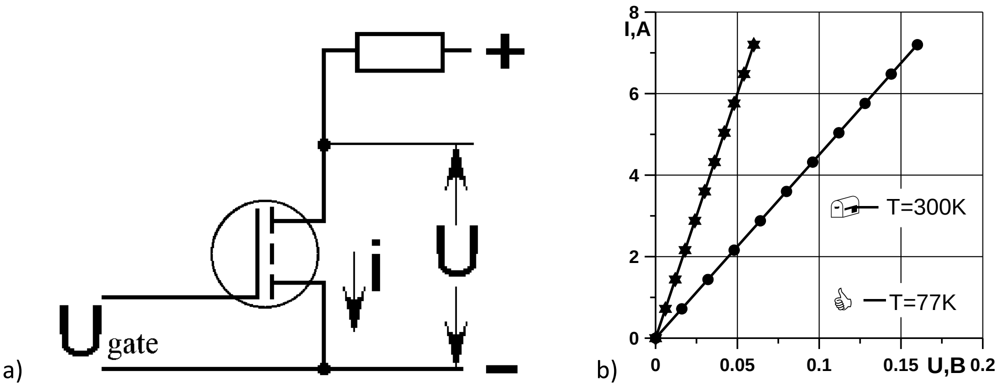

Figure 1. a) Electrical circuit of the experimental setup; b) output transistor saturation at room temperature T=300K and at liquid nitrogen temperature T=77K

To study the thermal characteristics of the transistor, it was placed on a radiator, which is an aluminium plate. Temperature sensors were installed on the surface of the transistor case and on the radiator. The structural layout of the transistor and photographs of the experimental setup are presented in the Figure 2 a, b, c, d.

The heat flux from the crystal of the semiconductor switch through the thermal resistance of the crystal-case enters the copper base of the transistor case and then through the thermal resistance of the case-radiator to an aluminium plate. Two temperature sensors installed on the transistor case and on the outside of the aluminium plate allow determining the distribution of heat along the entire heat flux path from the semiconductor crystal to the surface of the refrigerant (liquid nitrogen). Special sensors of the DT-621-HR type based on silicon diodes were used as temperature sensors.

The transistor with a radiator is placed in a foam box, which is filled with liquid nitrogen. The values of the voltage drop across the transistor, which actually functions as a heater and is in a linear mode, as well as the current through it, were measured. An increase in the voltage at the transistor led to an increase in the transistor current and the loss power released in it. Measurements were taken until the maximum heat flux density q was reached in accordance with the boiling curve $q = f(\Delta T)$.

When power is allocated in the switch, heat flow is transmitted through the aluminium plate to the refrigerant, as a result of which the process of boiling liquid nitrogen occurs. It is customary to characterize boiling modes (Grigoriev, Pavlov, Ametistov, 1977) as a function of the density of the heat flux q removed by the liquid from the heating surface on the temperature difference between the heating surface and liquid saturation ΔT. The boiling curve of liquid nitrogen shown in the Figure 3 in logarithmic coordinates is for all known liquids, including cryogenic (Grigoriev, Pavlov, Ametistov, 1977).

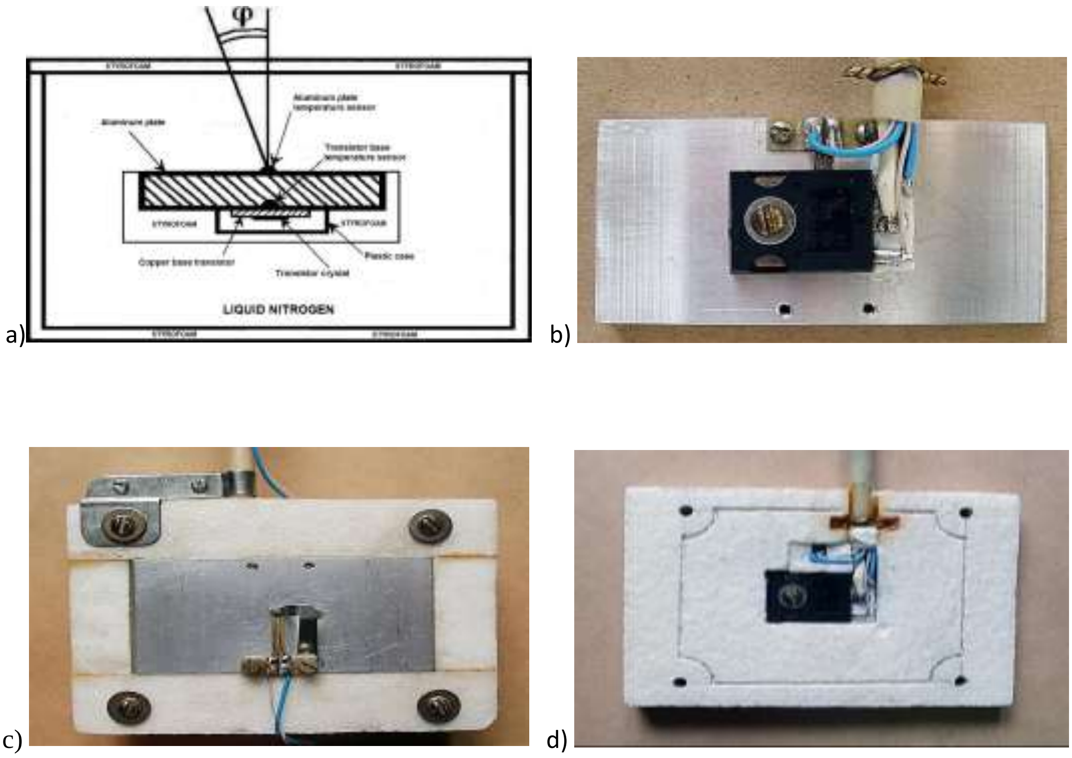

Figure 2. Experimental setup: a) experimental design; b) field effect transistor mounted on a heat-conducting aluminium plate; under the transistor at its base there is a temperature sensor; c) outer surface of the aluminium plate in contact with liquid nitrogen. In the center of the plate there is a temperature sensor; d) polystyrene covered aluminium plate with transistor

ISSN 2322- 6307

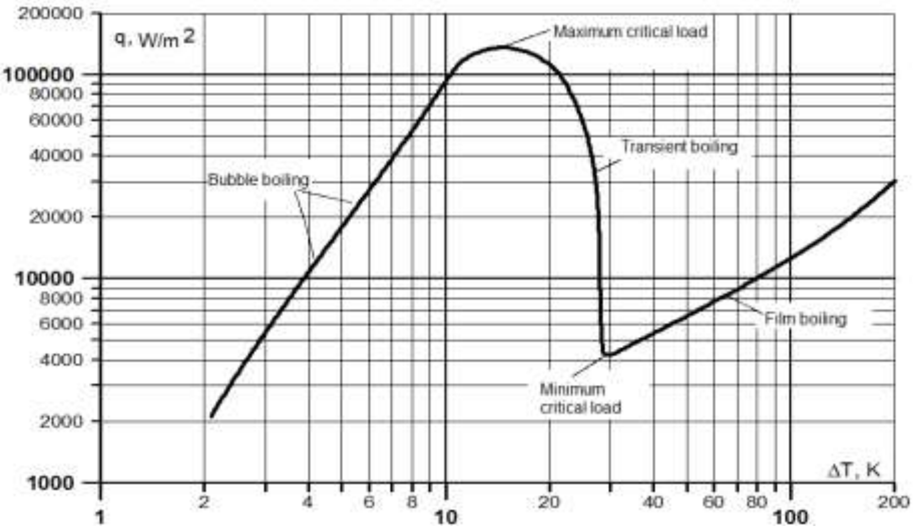

Figure 3. Liquid nitrogen boiling curve

There are three main areas on the curve. Here the study was conducted in the area of bubble boiling. At the point of maximum critical load, the process of increasing the power was stopped, since at this point the steam columns (bubbles), merging with each other, form a large bubble that impedes effective cooling (the first point of the boiling crisis). To this point, the switch current was increased.

Based on the measurement results, the power loss P_d, W, heat flux density q, W/cm^2, heat transfer coefficient $\alpha = q/\ \Delta T$, W/cm^2 K, thermal resistance $R = \Delta T/\ P_d$ °C/W were calculated.

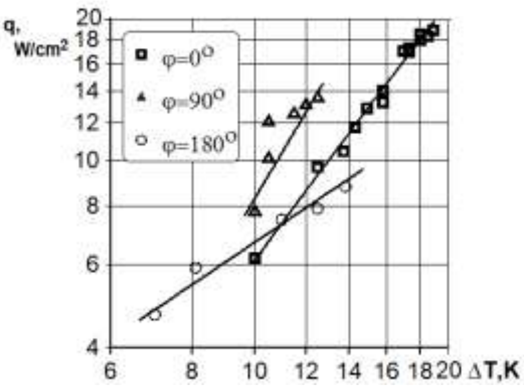

Figure 4. Dependence of heat flux density on temperature head at various positions of the cooling plate

The experiment was conducted for three positions of the investigated system: horizontal (□ in the Figure 4), vertical (Δ in the Figure 4) and reverse (flipped 180º relative to the first option, ○ in the Figure 4) one. A comparison of changes in the heat flux density during heating for the three indicated cases is presented in the Figure 4 on a logarithmic scale.

The maximum heat flux intensity corresponds to the vertical position of the system (middle straight line), and the minimum corresponds to the reverse position (lower straight line), which corresponds to generally accepted physical ideas about the heat transfer process (Naivelt, 1985).

The values of thermal resistance of the transition “radiator surface - refrigerant” were calculated. The minimum values of the average ones of this resistance are used with the vertical position of the system, and the maximum values are used with the reverse ones. It is obvious that with the vertical position of the system, the cooling rate of the switch increases, which leads to a decrease in thermal resistance R.

According to the results of experimental studies and calculations, we can take the average value of the coefficient of heat transfer from the surface of aluminium in a liquid nitrogen as $\alpha \sim 0{,}5\ W/cm^2$ K. Thus, when cooling with liquid nitrogen, the heat transfer coefficient is 3-4 orders of magnitude higher than with air convective cooling, since the coefficient α at room temperature does not exceed 0,003 W/cm^2 K (Naivelt, 1985).

An estimated calculation of the thermal process for the transistor type IRFP90N20D in the housing TO-247, placed on an aluminium plate with a total area of both sides S = 50 cm^2 (aluminium plate 50 x 50 x 5 mm) in liquid nitrogen.

From the technical data on the transistor, its thermal resistance is crystal-case is $R_{t\ cr\text{-}c}$ = 0,26 °C/W, and the typical value of the thermal resistance of the housing-heat sink and the typical value of the thermal resistance of the housing-heat sink $R_{t\ h\text{-}hs}$ = 0,24 º C /W (Infineon, 2016).

If α=0,5 W/cm^2 and S = 50 cm^2, thermal resistance radiator-environment is $R_{t\ c\text{-}e}$ = 0,04 ° C /W. The problem of determining the pattern of the thermal field was not solved, and the temperature of the surface of the heat sink was assumed to be the same, which is quite true for the indicated dimensions of the aluminium plate. The equivalent thermal equivalent circuit of the installation is shown in the Figure 5.

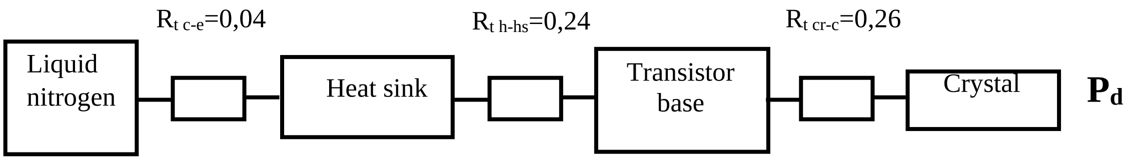

Figure 5. Equivalent thermal installation equivalent circuit

Table 1. Calculated values of temperatures T and temperature drops Q for various values of power losses P_l, allocated in the cristal

T_{av}	Q_{c-e}	T_{hs}	Q_{h-hs}	T_h	Q_{cr-c}	T_{cr}	P_l
-196	8	-188	48	-140	52	-88	200
-196	12	-184	72	-112	78	-34	300
-196	16	-180	96	-84	104	20	400
-196	20	-176	120	-56	130	74	500

The experimental value of the thermal resistance of the housing-heat sink $R_{th\text{-}hs}$ turned out to be slightly larger than the typical value and turned out to be 0.5 °C / W, which is apparently caused by the roughness of the surface of the heat-removing plate, the absence of heat-conducting paste, etc.

Table 2. Calculated values of temperatures T and temperature drops Q at various values of the power loss P l, secreted in the crystal, and the information about if R t h-hs = 0,5 º C /W

T_{av}	Q_{c-e}	T_{hs}	Q_{h-hs}	T_h	Q_{cr-c}	T_{cr}	P_l
-196	8	-188	100	-88	52	-36	200
-196	12	-184	150	-34	78	44	300
-196	16	-180	200	20	104	124	400
-196	20	-176	250	74	130	204	500

ISSN 2322- 6307

The calculation results for rows 3.4 from the Table 1 and row 3 from the Table 2 are presented in the Figure 6.

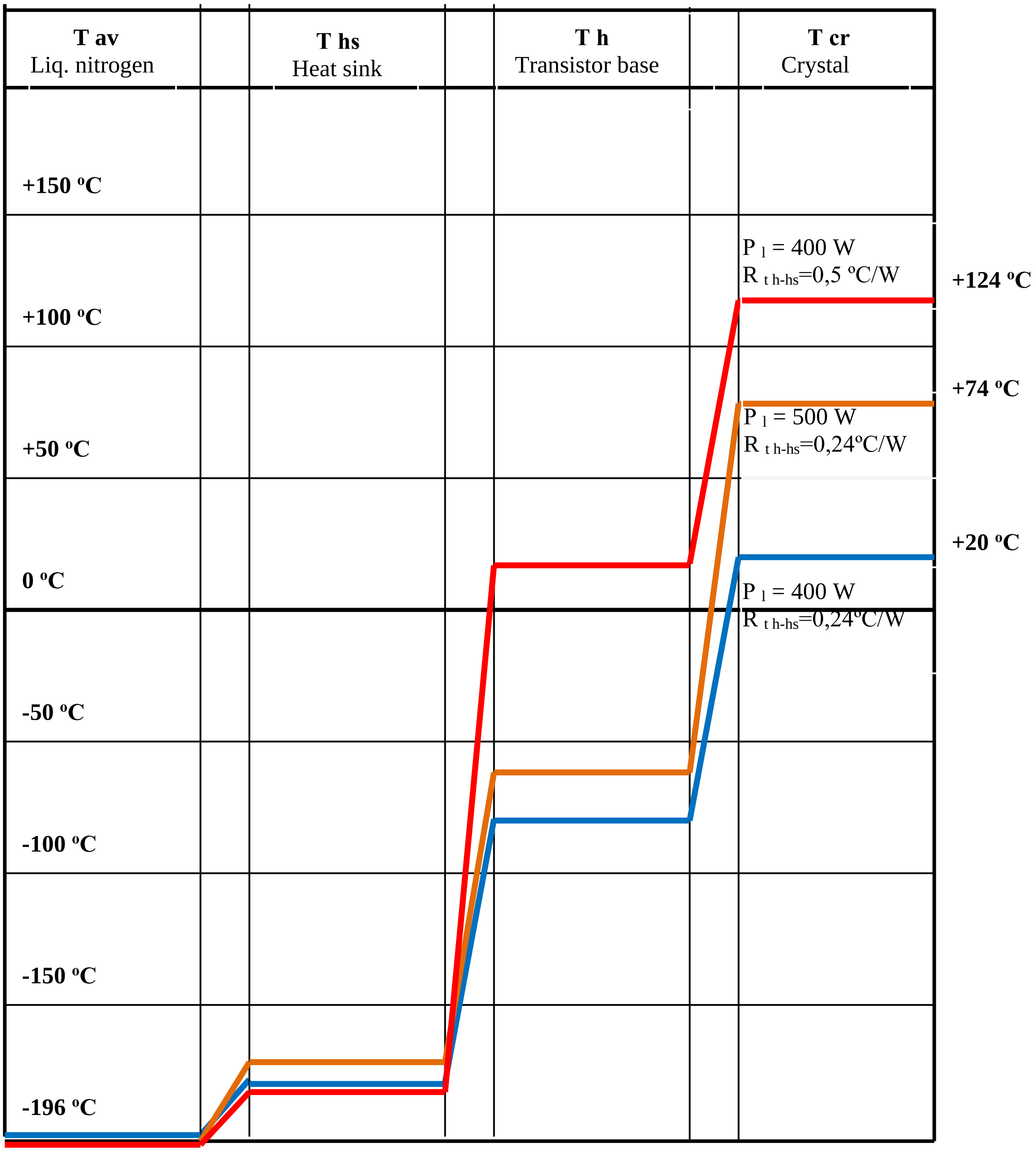

Figure 6. Temperature distribution diagram in the structure of crystal-liquid nitrogen

This diagram shows that when cooled with liquid nitrogen, the crystal temperature does not exceed the permissible temperature (175 ° C) (Infineon, 2016) with significant power losses. With convective cooling at room temperature (20° C), the crystal heating would be exceeded by 216° C compared to the temperatures shown in Figure 6 in the right column, since the crystal temperature is determined by the formula (Chebovsky, Moiseev, Nedoshivin, 1985) $T_{cr} = T_{env} + R_t P_l$, where R_t is the total transient thermal resistance crystal - environment, P_l is the power loss.

All of the above indicates the benefits of implementing cryogenic cooling of secondary power sources. It is advisable to carry out power converters using modern powerful semiconductor devices, primarily diodes, thyristors, bipolar and field effect transistors, since powerful devices have the best overall dimensions.

When developing systems containing, having electromechanical and power converters, a number of specific problems arise, the solution of which determines the efficiency of the systems. The first problem is the influx of heat into the cold zone due to powerful current leads. The last problem is illustrated in the Figure 7, where, as an example, there is a system for transmitting electricity from a superconducting synchronous generator through a superconducting cable.

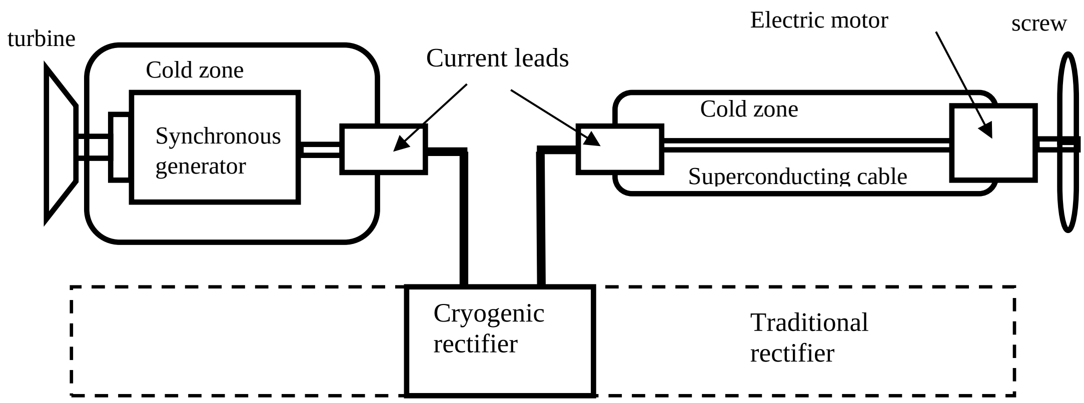

Figure 7. Isolated position of the rectifier in the electric transmission of the aircraft

It can be seen from the figure that the location of the converter (rectifier) outside the cold zone requires additional powerful current inputs through which heat is supplied to the cold zone.

Figure 8 shows a similar power transmission system with the conversion of electric parameters when the converter is located in a cold zone.

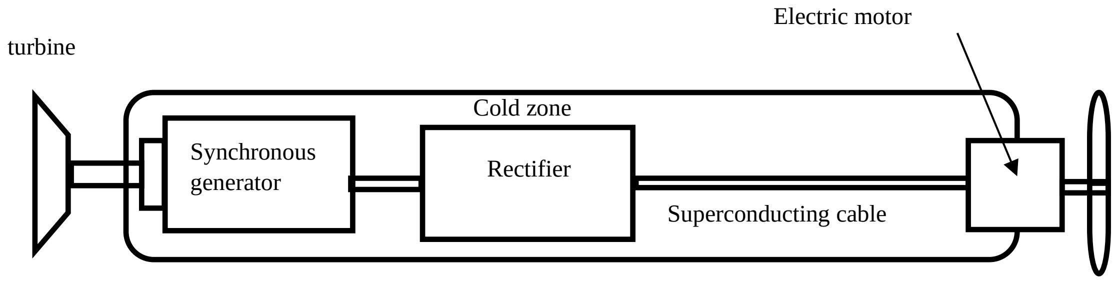

Figure 8. Integrated rectifier position in an electric aircraft transmission

As follows from (Kostyuk, Katorgin, Firsov, Kovalev, Ravikovich, Antyukhov, Timushev, Vereshchagin, Kholobtsev, Ermilov, Balaboshko, Gapeev, Lesovnikov, Sychkov, Modestov, 2017), the placement of the entire converter unit in the cooling zone is much more promising, since the influx of heat into the cold zone is reduced by reducing the number of current leads.

To confirm the prospect of cryogenic cooling of semiconductor devices, a DC-voltage converter, including an inverter and a rectifier, was manufactured and tested without changing the value of the output voltage in order to evaluate the overall dimensions of the converter unit when placed in a cryogenic medium. A general view of the electrical connections of the installation is shown in the Figure 9. With a intput power of 10 kW, the efficiency of the installation was 97 %.

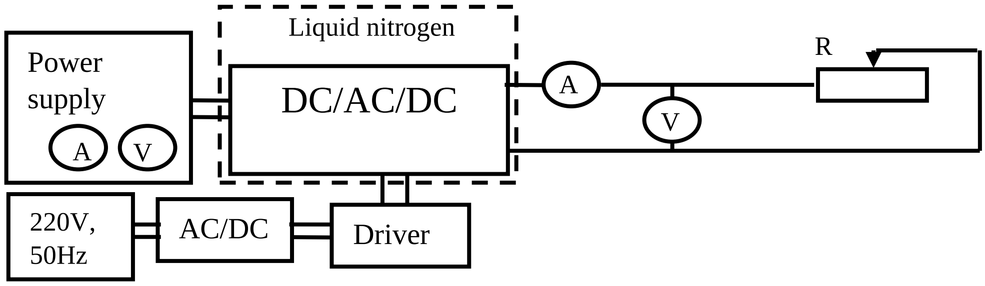

Figure 9. Measurement scheme for the efficiency and losses of a cryogenic semiconductor unit with double energy conversion

Expected increase in the specific power of the power converter under cryogenic cooling is determined by the following factors: decrease in the weight of radiators and increase in the current load of the switches.

Surface area of the radiator is inversely proportional to the heat transfer coefficient α (1). If, under convective cooling by air, the value of α is 5÷30 Вт/м^2 K (Naivelt, 1985), then upon cooling with liquid nitrogen, as was shown above as a result of the experiment, the value of the heat transfer coefficient increases to 10^4 W/m^2 K. The mass of the M_{cool} plate radiator can be estimated by the following expression: $M_{cool} = 0{,}5P_l\ \rho\ \delta/\ \alpha\ \Delta T$, where δ and ρ are the thickness of the radiator plate and the specific gravity of the material from which it is made.

The current load of the switch, as it is known, is limited by the maximum permissible temperature of its crystalline semiconductor transition T_{sc}. The value of T_{sc} is calculated using the well-known expression (Chebovsky, Moiseev, Nedoshivin, 1985): $T_{sc} = T_{amb} + R_{warm}\ P_l$, where T_{amb} is the ambient temperature, R_{warm} is the total thermal resistance of the crystal-environment part. Assuming that the transistor operates in switching mode at a low conversion frequency, its losses will be mainly determined as (Naivelt, 1985) $P_l = I\ \Delta U$, where I is the transistor current, ΔU is the voltage drop across the transistor when open.

Taking into account (4) and (5), current load of the transistor can be determined as follows: $I = (T_{sc} - T_{amb})/\ R_{warm}\ \Delta U$.

Considering the above results of the experiments, using (3) and (6), we can make a preliminary estimate of the relative mass of the semiconductor converter with cryogenic cooling. Taking into account a significant reduction in the mass of radiators and an increase in the installed power of a single switch, expected value of the specific mass of the converter can be about 0,01÷0,02 kg/kW, which, in terms of specific power, will be 50÷100 kW/kg.

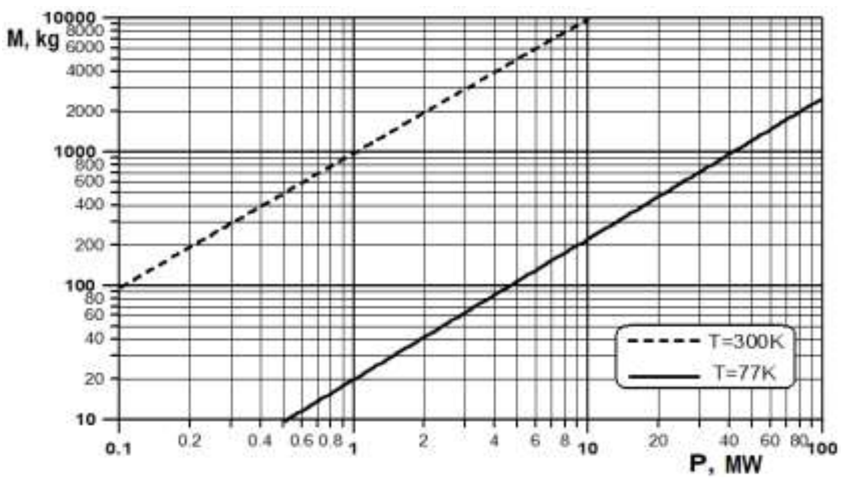

Figure 10. Expected mass values of the power convertor versus output power at different cooling temperatures

Figure 10 shows, considering expected values of the specific power, mass of power converter versus output power at different cooling temperatures (at room temperature T = 300 K and at liquid nitrogen temperature T = 77 K). In this case, the minimum values of specific power from the above range were considered.

With a limited amount of refrigerant, the duration of the converter will be limited due to the boiling of the refrigerant. This problem can be solved either by significantly increasing the efficiency of the device, or by organizing the pumping of refrigerant due to modern closed-loop cryogenic systems (Kostyuk, Katorgin, Firsov, Kovalev, Ravikovich, Antyukhov, Timushev, Vereshchagin, Kholobtsev, Ermilov, Balaboshko, Gapeev, Lesovnikov, Sychkov, Modestov, 2017).

Conclusion

1. The results of the experiments showed the efficiency of cryogenic cooling of semiconductor switches, which is caused by a significant increase (by several orders of magnitude) of the heat transfer coefficient and, as a result, a decrease in the mass and dimensions of radiators, and therefore the entire converter.
2. Calculations based on the results of the experiment showed that the use of cryogenic cooling makes it possible to increase the specific power of the converter approximately 50÷100 times.
3. Consideration of the layout of the converter unit showed that the placement in the cooling zone is the most promising.
4. In the future, it is planned to compare experimental data and theoretical models on prototypes.

«This work was financially supported by the Ministry of Science and Higher Education of the Russian Federation within the state assignment (project № 8.7885.2017/8.9)».

References

Chebovsky O.G., Moiseev L.G., Nedoshivin R.P. (1985). Power semiconductor devices: Reference. Moscow: Energoatomizdat.

Dubensky A.A., Kovalev K.L., Larionoff A.E., Modestov K.A., Penkin V.T., Poltavets V.N. (2016). Outlook of the use of cryogenic electric machines onboard aircraft. IEEE Transactions on Applied Superconductivity. 26(3), 1-4.

Dubensky G.A., Kovan Yu.I. (2017). Electric power conversion devices. Moscow: Moscow Aviation Institute.

Grigoriev V.A., Pavlov Yu.M., Ametistov E.V (1977). Boiling cryogenic liquids. Moscow: Energy.

Infineon (2016). Infineon Technologies AG. Available at: http://www.irf.com/package/

Kostyuk V.V., Katorgin B.I., Firsov V.P., Kovalev K.L., Ravikovich Yu.A., Antyukhov I.V., Timushev S.F., Vereshchagin M.M., Kholobtsev D.P., Ermilov Yu.I., Balaboshko N.G., Gapeev Yu.A., Lesovnikov A.S., Sychkov A.E., Modestov K.A. (2017). Cryosupply system for high-temperature superconductivity of devices (SCR 001). Engineering Journal: Science and Innovation. 8, 1-27.

Kovalev K.L., Penkin V.T., Larionov A.E., Modestov K.A., Ivanov N.S., Tulinova E.E., Dubensky A.A., Verzhbitsky L.G., Kozub S.S. (2016). Brushless Superconducting Synchronous Generator with Claw-shaped Poles and Permanent Magnets. IEEE Transactions on Applied Superconductivity. 26(3), 1-4.

Levin A.V., Alekseev I.I., Kharitonov S.A., Kovalev L.K. (2010). Electric aircraft: from idea to implementation. Moscow: Mechanical Engineering.

Modestov K., Kovalev K., Dubensky A., Zhuravlev S. (2018). Brushless Nonsteel HTS Generator With Combined Excitation With Trapped Field Plates on the Rotor. IEEE Transactions on Applied Superconductivity. 28(4), 1-5.

Musin S.M. (2014). Electric airplane: concept and technology. Ufa: Ufa State Aviation Technical University.

Naivelt G.S. (1985). Power supplies for electronic equipment: guide. Moscow: Radio and Communications.

Ward R.R., Dawson W.J., Zhu L., Kirschman R.K., Mueller O., Hennessy M.J., Mueller E., Patterson R.L., Dickman J. E., Hammoud A. (2003). Power diodes for cryogenic operation in PESC Record. IEEE Annual Power Electronics Specialists Conference. 4, 1891-1896.